Photon Structure and Photoproduction at HERA

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on behalf of the H1 and ZEUS collaborations

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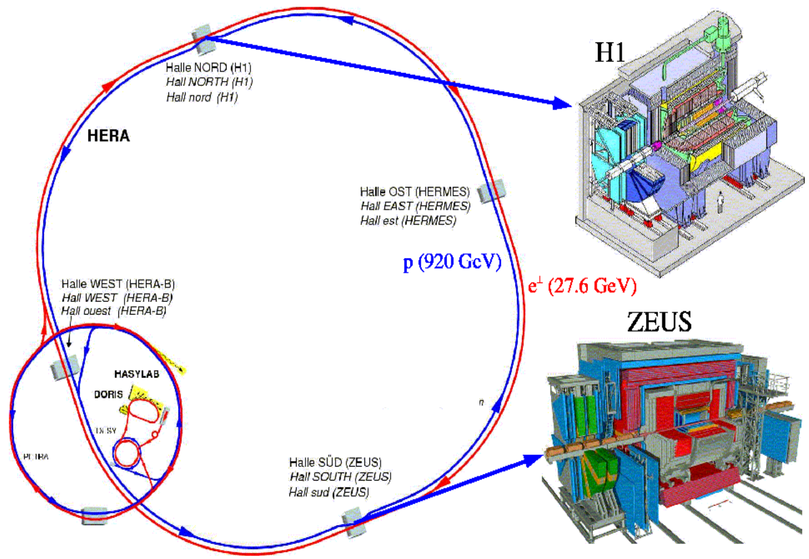
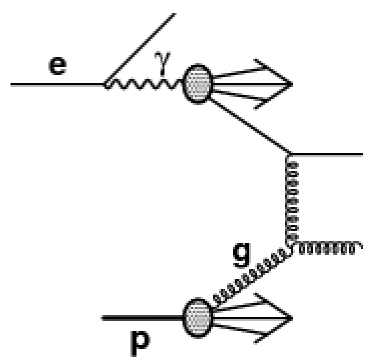
HERA - Introduction



Photoproduction

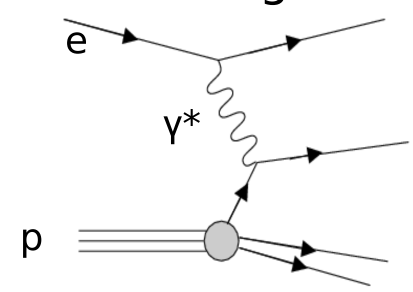


quasy real photon: $Q^2 \simeq 0$

Probe structure of the proton and photon

scattered electron not measured
in main detector

Deep Inelastic Scattering



high photon virtuality $Q^2 >> 1\ GeV^2$

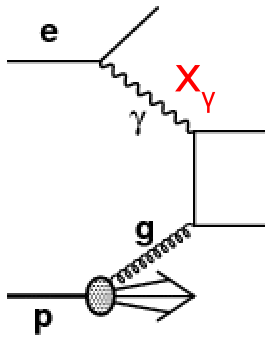
Probe structure of the proton

scattered electron in main detector

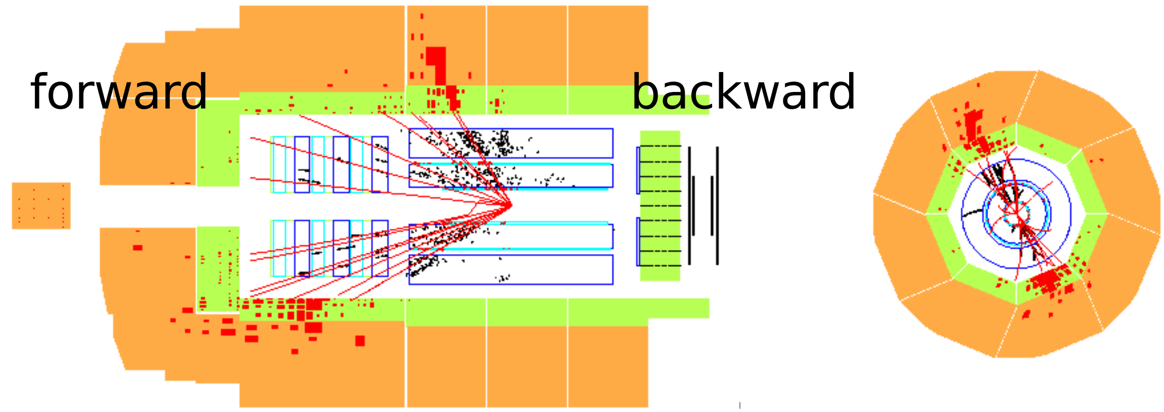
Photoproduction at HERA - Introduction

LO: direct
photon interacts directly

$x_\gamma=1$

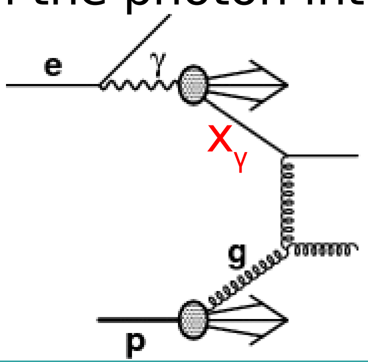


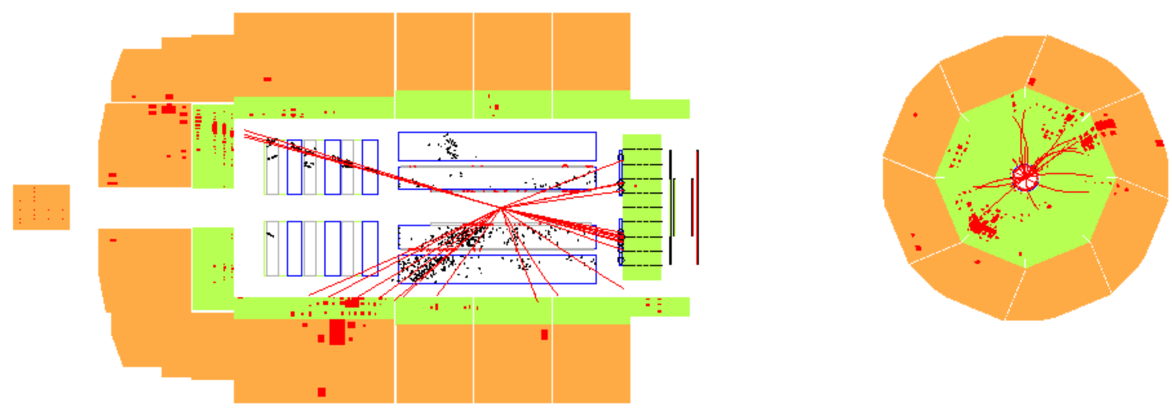
typical events with two hard jets



LO: resolved
partons from the photon interacts

$x_\gamma<1$



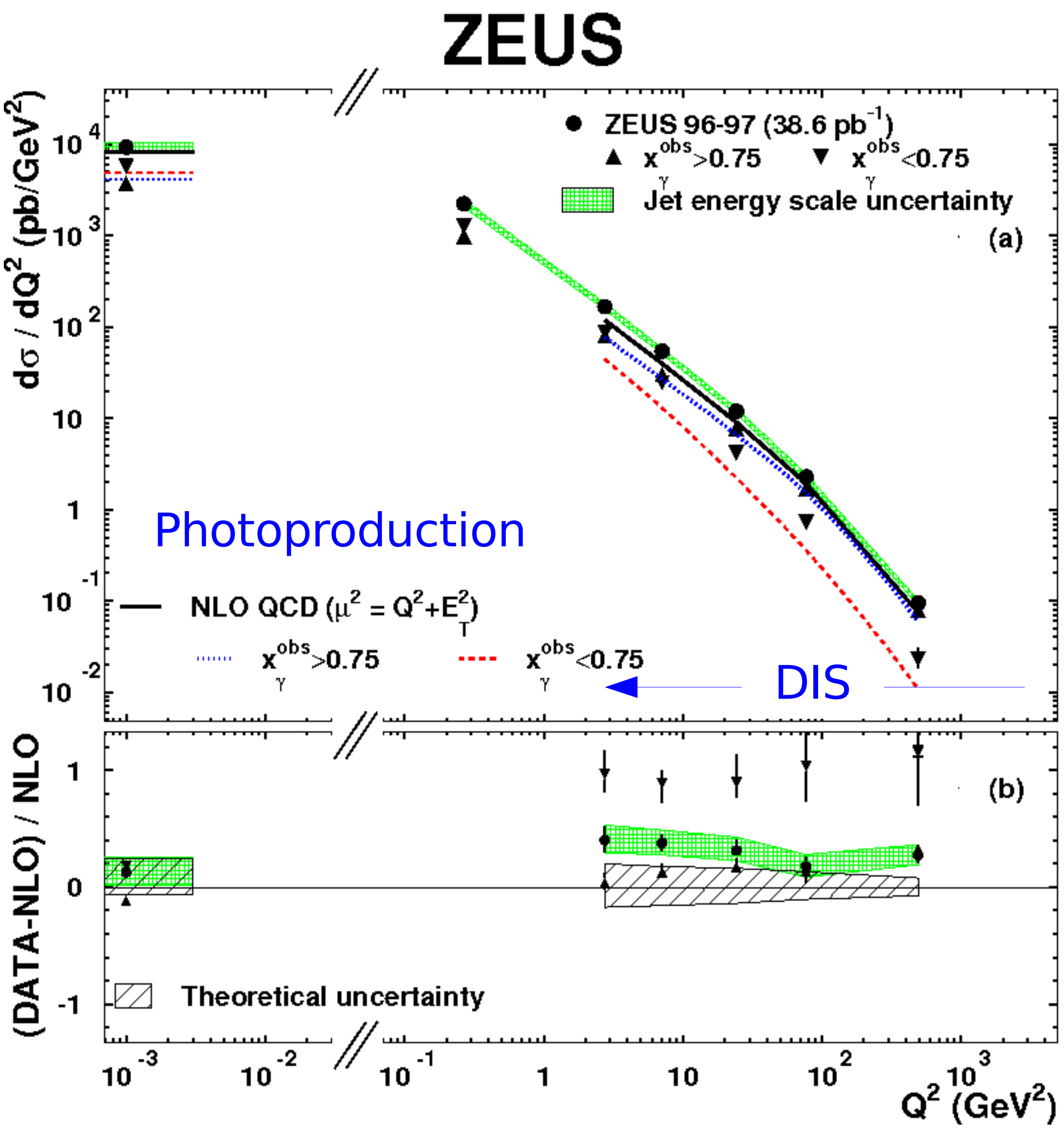


Probe structure of the photon with dijet events
x_γ fraction of photon longitudinal momentum entering hard process

$$x_\gamma^{obs} = \frac{E_T^{jet1}\exp(-\eta^{jet1}) + E_T^{jet2}\exp(-\eta^{jet2})}{2\,y\,E_e}$$

Jets: inclusive kt algorithm

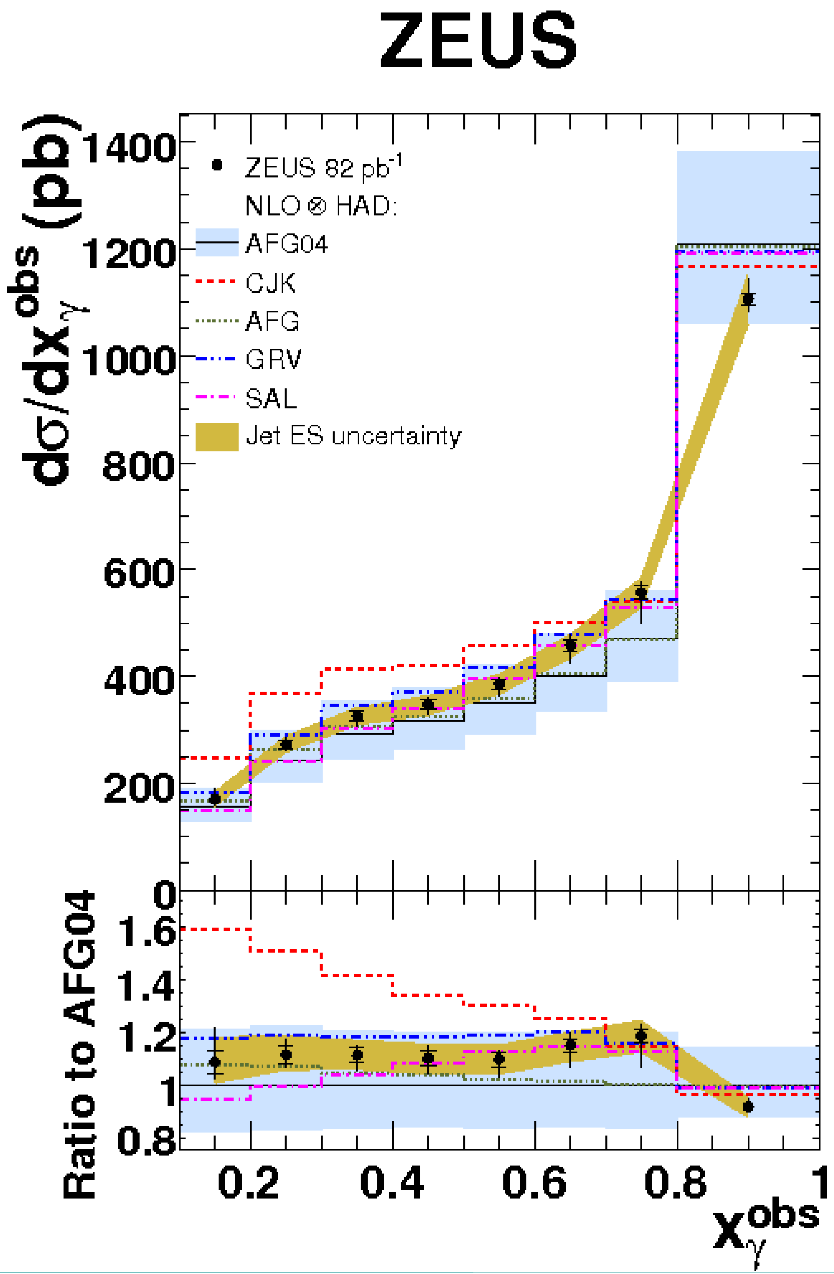
Q^2 Dependence of Dijet Cross Section



- Cross section falls by 5 orders
- NLO describes shape, 30% low
- x_γ^{obs} >0.75 well described
- x_γ^{obs} <0.75
  - drops faster with Q^2
  - Q^2>0 underestimated by NLO
  - 25% contribution at high Q^2
  - NLO uncertainty higher (30%)
- Q^2=0 agreement with NLO
  - low x_γ^{obs} dominant

hep-ex/0404033 ZEUS: 38.6 pb^{-1} ,0<Q^2<2000 GeV^2 jets: -3<$\eta^{\gamma p}$<0 , E_T^{Jet1}>7.5 GeV, E_T^{Jet2}>6.5 GeV

Dijets in Photoproduction: Sensitivity to Photon PDF



$$x_\gamma^{obs} = \frac{E_T^{jet1}\exp(-\eta^{jet1}) + E_T^{jet2}\exp(-\eta^{jet2})}{2\,y\,E_e}$$

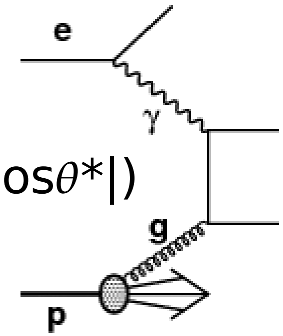
- Data: energy scale main syst. error
- High x_γ^{obs}
  predictions from different PDFs similar
- Low x_γ^{obs}
  Sensitivity to different photon PDFs

  differences up to 70%
- $x_\gamma^{obs} \gtrsim 0.8$ direct dominated
- $x_\gamma^{obs} \lesssim 0.8$ resolved dominated

arXiv:0706.3809 [hep-ex]] ZEUS: 81.8 pb^{-1}, $Q^2<1$ GeV^2, $142<W^{\gamma p}<293$ GeV, $-1<\eta^{jet}<3$, $E_T^{Jet1}>20$ GeV, $E_T^{Jet2}>15$ GeV

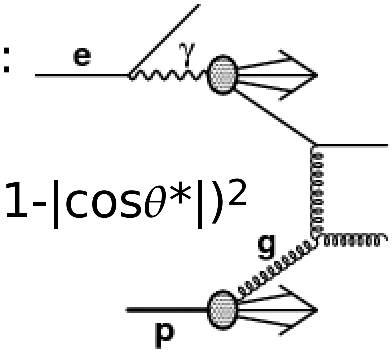
Photon Structure – direct vs. resolved processes

Direct:



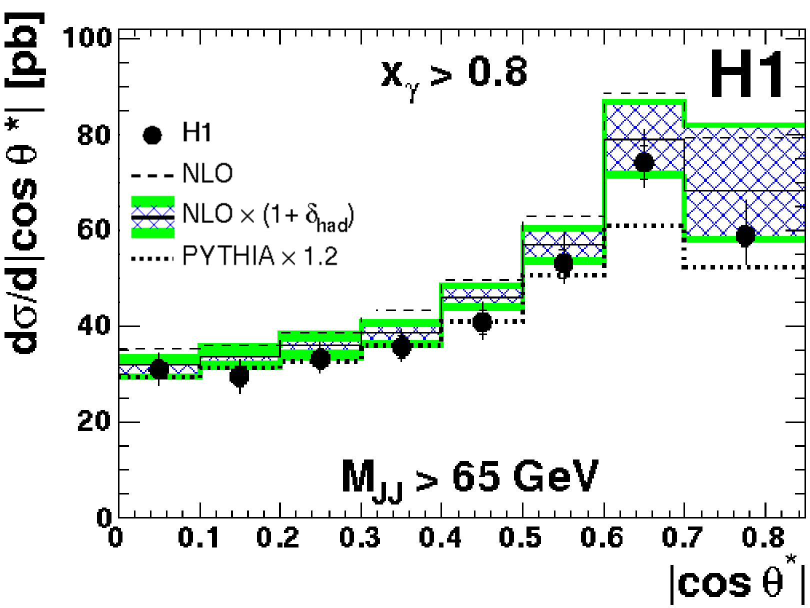
$1/(1-|\cos\theta^*|)$

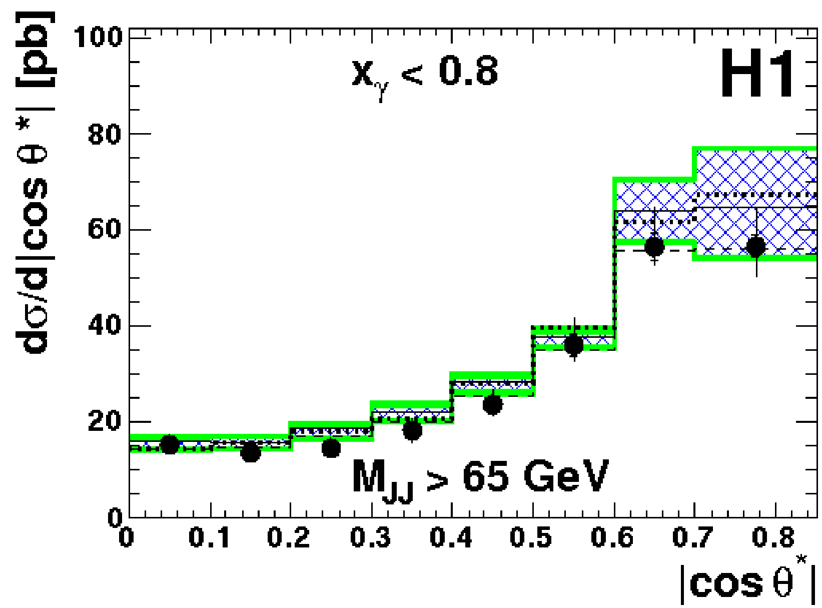
Resolved:



$1/(1-|\cos\theta^*|)^2$

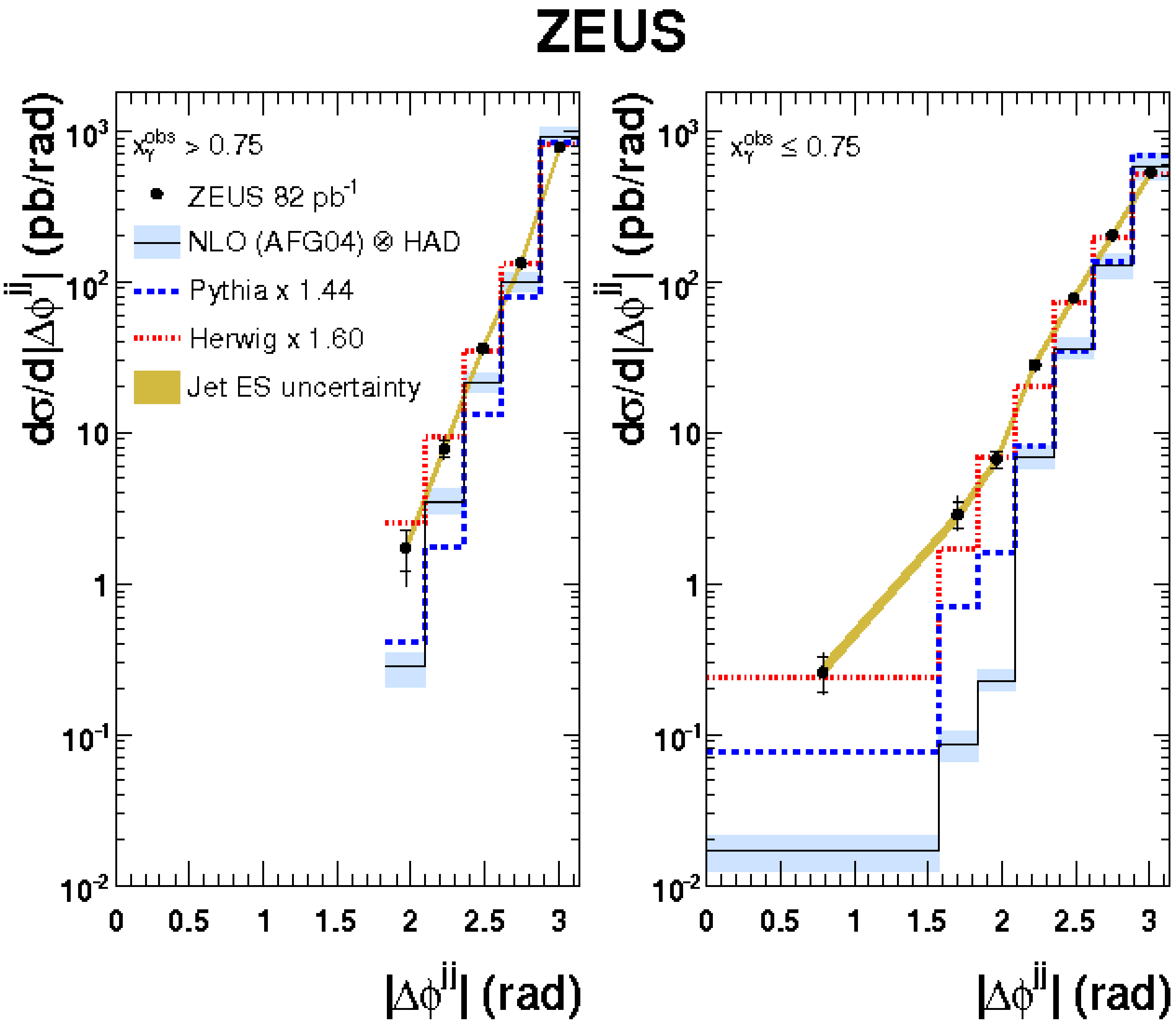
CMS scattering angle $\cos\theta^* = \tanh((\eta^1-\eta^2)/2)$ sensitive to dynamics of hard interaction





- Resolved enhanced: cross section rises more rapidly
- Confirms dominating gluon propagator

hep-ex/0603014 H1: 66.6 pb^{-1}, Q2<1 GeV^2, $0.1<y<0.9$, $-0.5<\eta^{jet}<2.75$, $E_T^{Jet1}>25$ GeV, $E_T^{Jet2}>15$ GeV



- NLO: back-to-back: well described
- LO MC: scaled

- x_γ^{obs} >0.75: direct enhanced
  - x-sec less steep NLO and PYTHIA

- x_γ^{obs} <0.75: resolved enhanced
  - NLO much too steep, below the data
  - PYTHIA: poor description

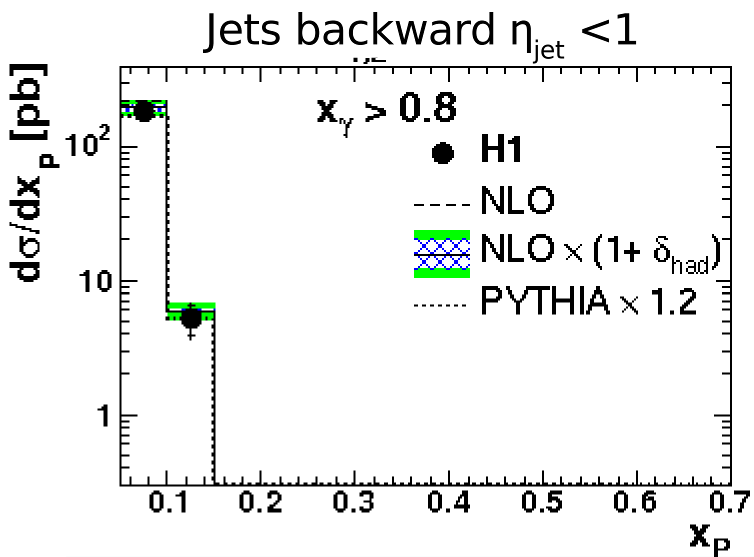
HERWIG: good description shower treatement better to account for HO effects

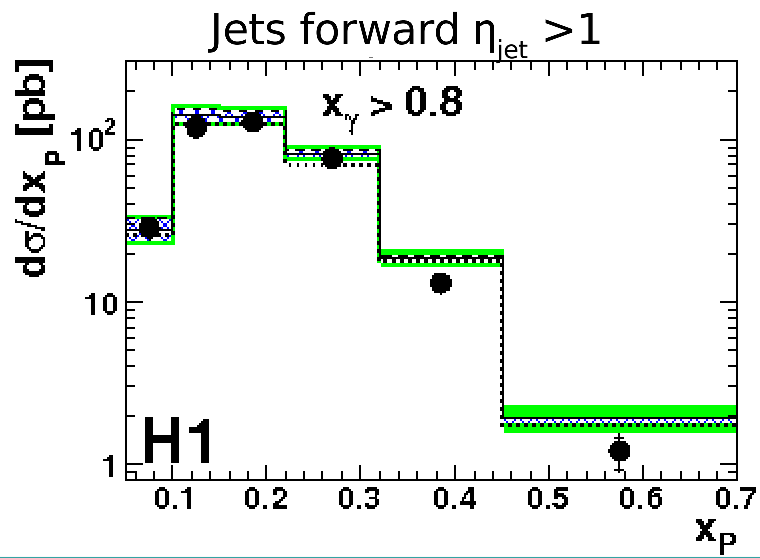
arXiv:0706.3809 [hep-ex]] ZEUS: 81.8 pb^{-1}, Q^2<1 GeV^2, 142<$W^{\gamma p}$<293 GeV, -1<η^{jet}<3, E_T^{Jet1}>20 GeV, E_T^{Jet2}>15 GeV

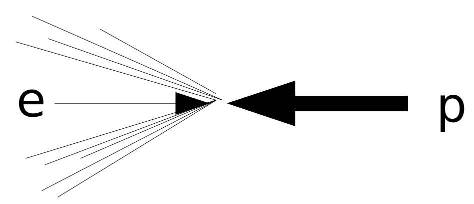
Jet Topologies: Proton Momentum Fraction

x_p: momentum fraction carried by parton of proton

$$x_p^{obs} = \frac{E_T^{jet1} \exp(\eta^{jet1}) + E_T^{jet2} \exp(\eta^{jet2})}{2 E_p}$$





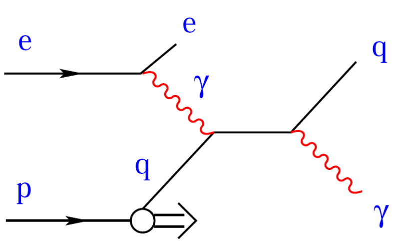


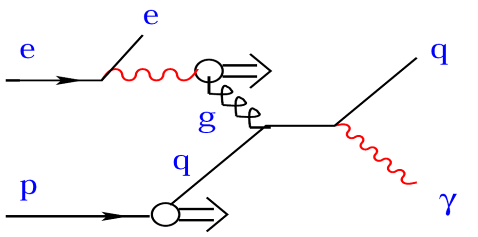
- Direct enhanced sample, results for resolved enhanced similar
- NLO, PYTHIA: overall good description, except highest x_p
- Forward-forward topology: access to high x_p
- PDF uncertainty largest for high x_p(green)

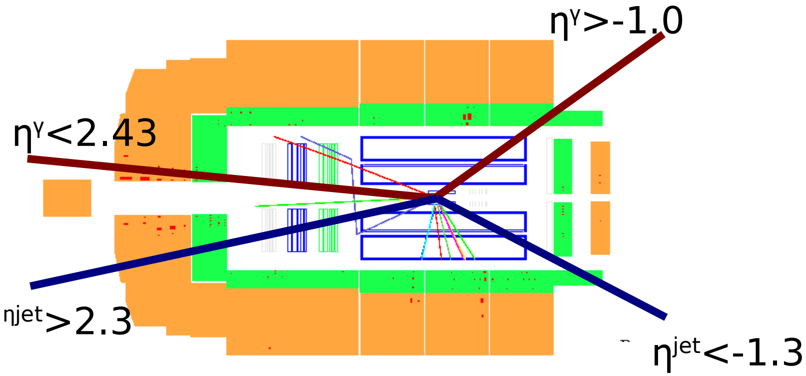
hep-ex/0603014 H1: 66.6 pb^{-1}, Q2<1 GeV^2, 0.1<y<0.9, -0.5<η^{jet}<2.75, E_T^{Jet1}>25 GeV, E_T^{Jet2}>15 GeV

Prompt Photons in Photoproduction

In addition to direct and resolved contributions: quark-to-photon fragmentation





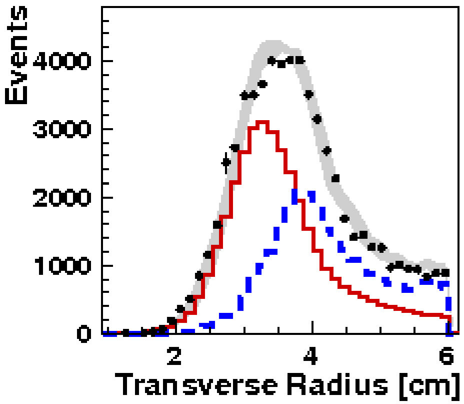


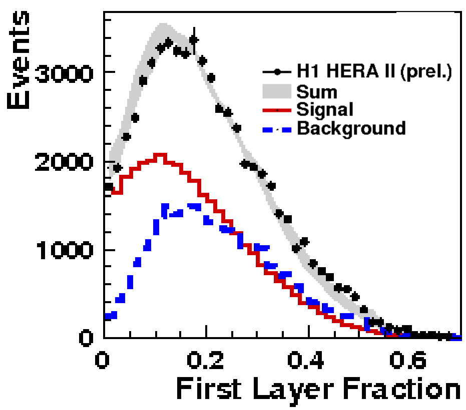
- Alternative access to x_γ and x_p
- Different systematics
- Smaller corrections for hadronisation
- New analysis extends to forward region

- $6 < E_T^\gamma < 15$ GeV
- $-1.0 < \eta^\gamma < 2.43$
- $0.1 < y < 0.7$
- Isolation $z = E_T^\gamma / E_T^{photon\text{-}jet} > 0.9$

Exclusive photon plus jet

- $4.5 < E_t^{jet}$
- $-1.3 < \eta^{jet} < 2.3$

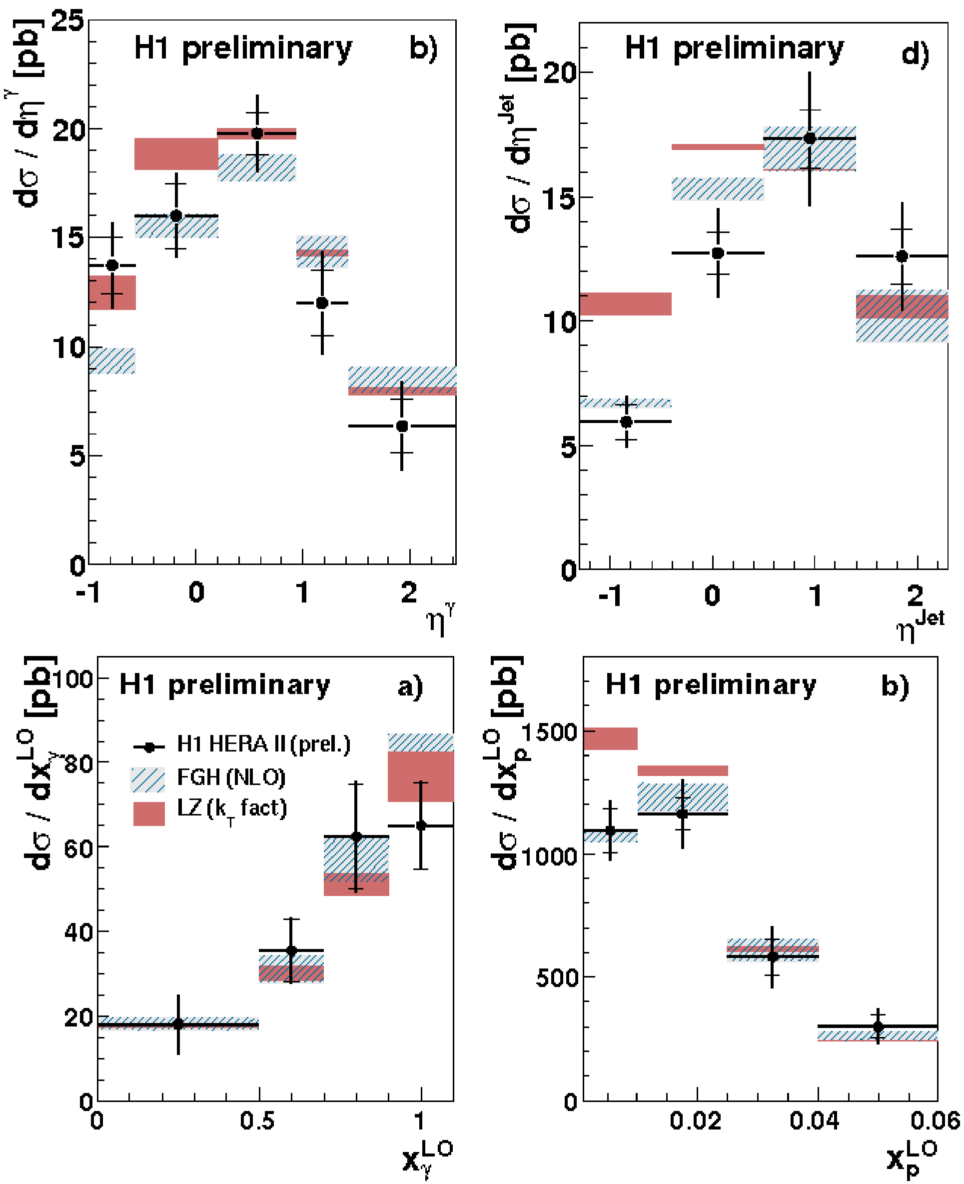




Separation from background: shower shape

H1 preliminary 09-035

Prompt Photon plus Jet Cross Section



Comparison to
NLO calculation (FGH)
kt factorisation approach (LZ)

FGH low for backward photons
LZ does not describe the jets

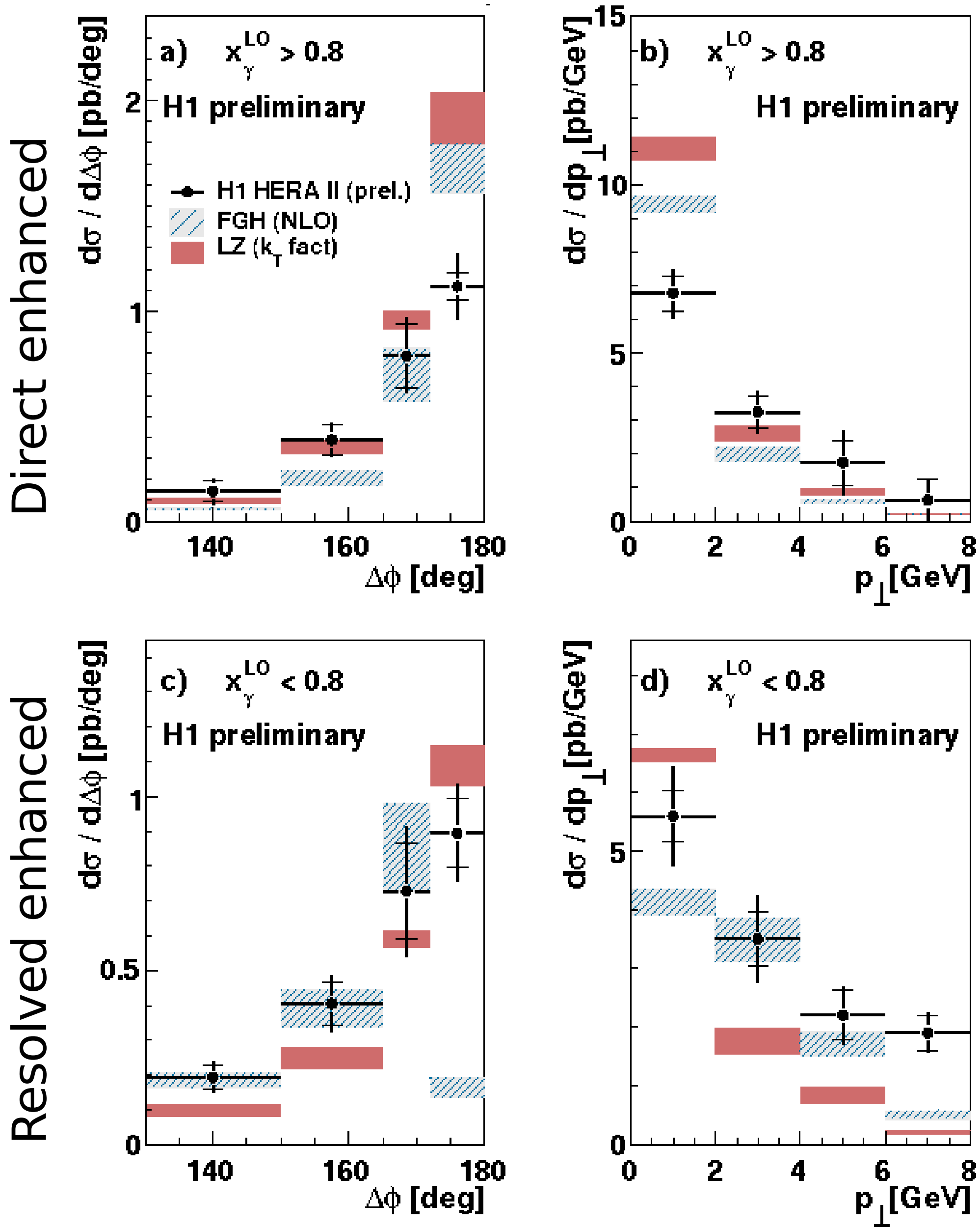
$$x_{\gamma}^{LO} = E_T^{\gamma} \frac{\exp(-\eta^{\gamma}) + \exp(-\eta^{jet})}{2\, y\, E_e}$$

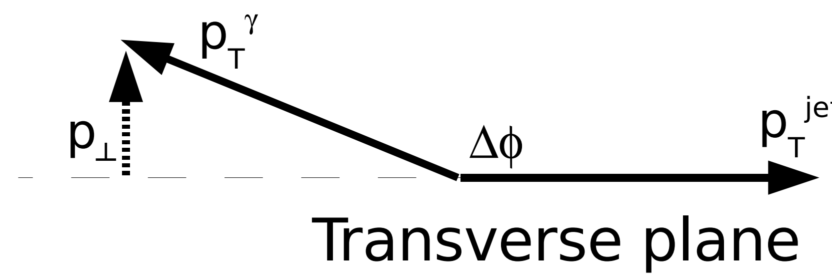
$$x_{p}^{LO} = E_T^{\gamma} \frac{\exp(\eta^{\gamma}) + \exp(\eta^{jet})}{2\, E_p}$$

Reasonable description by the calculations
LZ problems at low x_p – overshoot at low η^{jet}

H1 preliminary 09-035 $\quad 6 < E_T^{\gamma} < 15$ GeV, $-1.0 < \eta^{\gamma} < 2.43$, $0.1 < y < 0.7$, $4.5 < E_t^{jet}$, $-1.3 < \eta^{jet} < 2.3$

Prompt Photon and Jet: Transverse Correlation





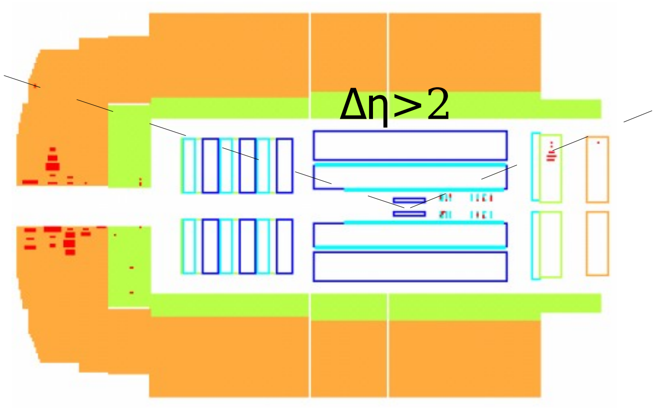
- $x_\gamma > 0.8$
  Both calculations overestimate
  back-to-back configuration

- $x_\gamma < 0.8$
  multiple soft gluon emission:
  NLO not valid in last bin ΔΦ
  LZ does underestimates tails

Reminder dijets:
  back-to-back well described
  NLO steeper than data

H1 preliminary 09-035 $6 < E_T^\gamma < 15$ GeV, $-1.0 < \eta^\gamma < 2.43$, $0.1 < y < 0.7$, $4.5 < E_t^{jet}$, $-1.3 < \eta^{jet} < 2.3$

Diffractive Scattering of high t Photons $e^+p \rightarrow e^+\gamma Y$

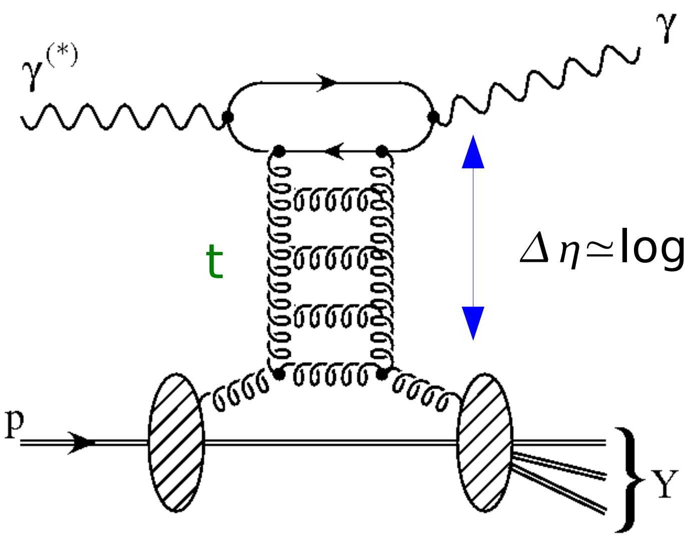


- Clean process
- Photoproduction with large t: hard scale
- Complements measurements with VM (J/ψ,ρ,φ)
- No VM wave function uncertainty
- Important test of the BFKL dynamics σ(W),dσ/dt
- Extends DVCS to small Q^2
- LLA BFKL calculation included in HERWIG

Kinematic recontruction

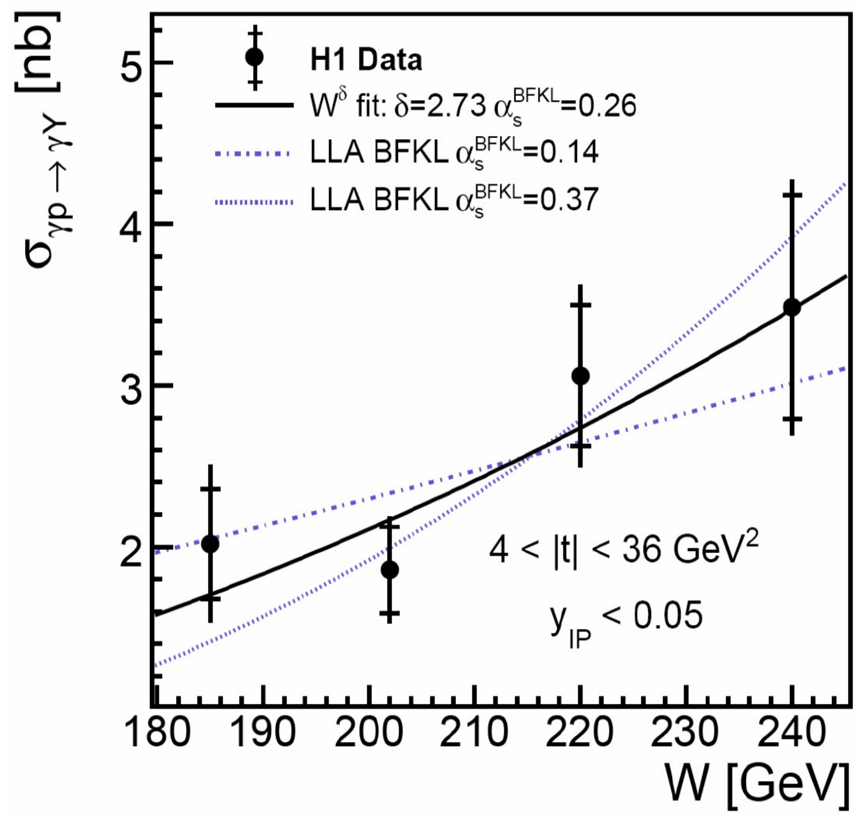
$$t=(q-p_X) \rightarrow |t|=(p_T^\gamma)^2$$

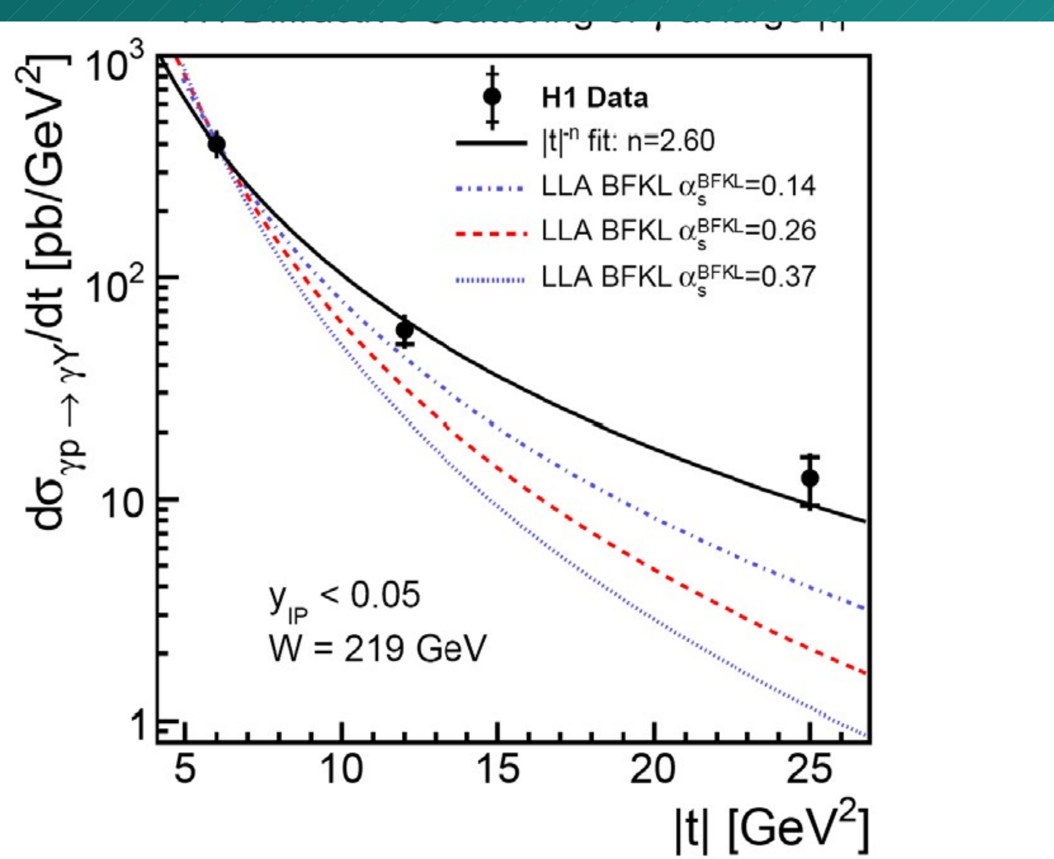
$$W^2=(1-\frac{E_{e'}}{E_e})\cdot s$$



[arXiv:0706.3809 [hep-ex]] 46.2 pb^{-1}, Q^2<0.01 GeV^2, 175 < W < 247, 4<|t|<36 GeV^2, y_{IP}<0.05, p_t^γ > 2 GeV, E^γ > 8 GeV, Δη>2

Diffractive Scattering of High t Photons $e^+p \to e^+\gamma Y$





rise of σ with W: fit: $\sigma \sim W^\delta$

δ=2.73 ± 1.02 (stat) $^{+0.56}_{-0.78}$ (syst)

<t>=6.1 GeV^2

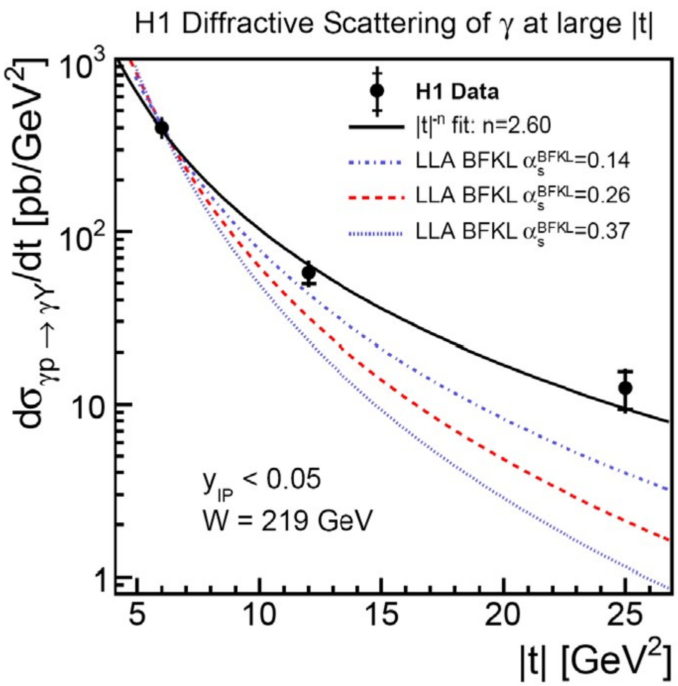
- δ compatible with J/Ψ data
  δ=1.29±0.23±0.16

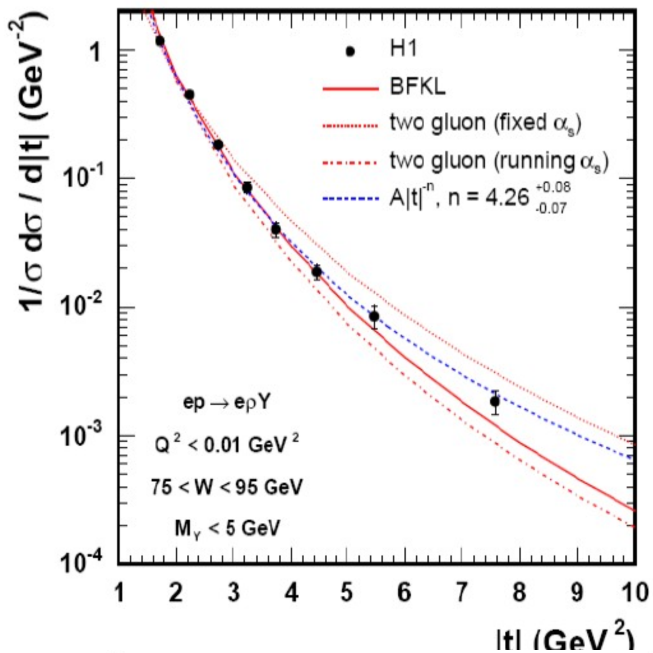
Fit: $d\sigma/dt \sim |t|^{-n}$

n=2.60 ± 0.19(stat) $^{+0.03}_{-0.08}$ (syst)

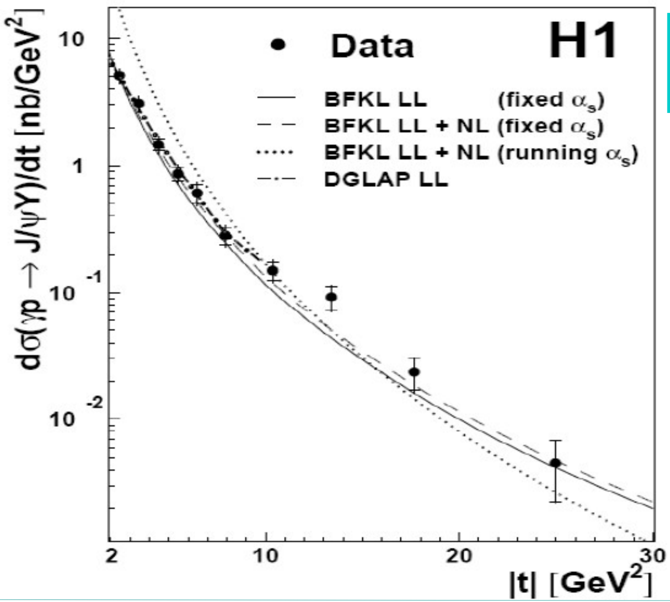
- $|t|$ distribution harder than LLA BFKL
- harder than for vector mesons

[arXiv:0706.3809 [hep-ex]] 46.2 pb^{-1}, Q^2<0.01 GeV^2, 175 < W < 247, 4<|t|<36 GeV^2, y_{IP}<0.05, p_t^γ > 2 GeV, E^γ > 8 GeV, Δη>2





ρ



J/ψ

$d\sigma/dt \sim |t|^{-n}$

Photons: $n=2.60 \pm 0.19(\text{stat})\,^{+0.03}_{-0.08}\,(\text{syst})$

ρ: $n= 4.26^{+0.08}_{-0.07}$

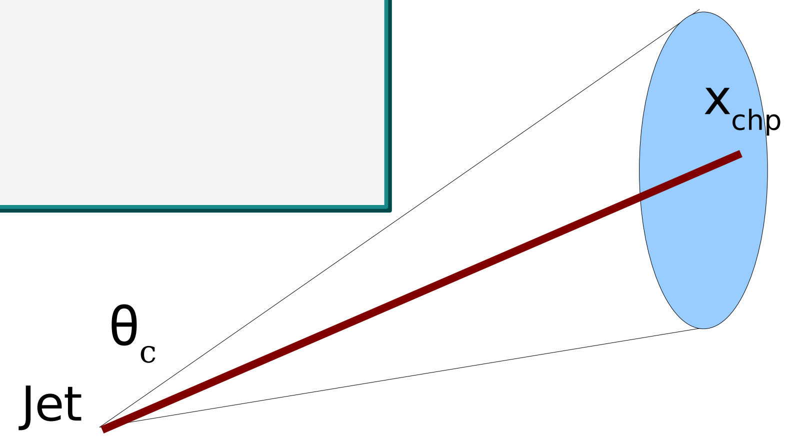
J/ψ $n= 3.78 \pm 0.17 \pm 0.06$

harder than for J/Ψ or ρ

[arXiv:0706.3809 [hep-ex]] 46.2 pb^{-1}, $Q^2<0.01$ GeV^2, 175 < W < 247, 4<|t|<36 GeV^2, $y_{IP}<0.05$, $p_t^{\gamma} > 2$ GeV, $E^{\gamma} > 8$ GeV, Δη>2

Soft Particle Distribution in Photoproduction

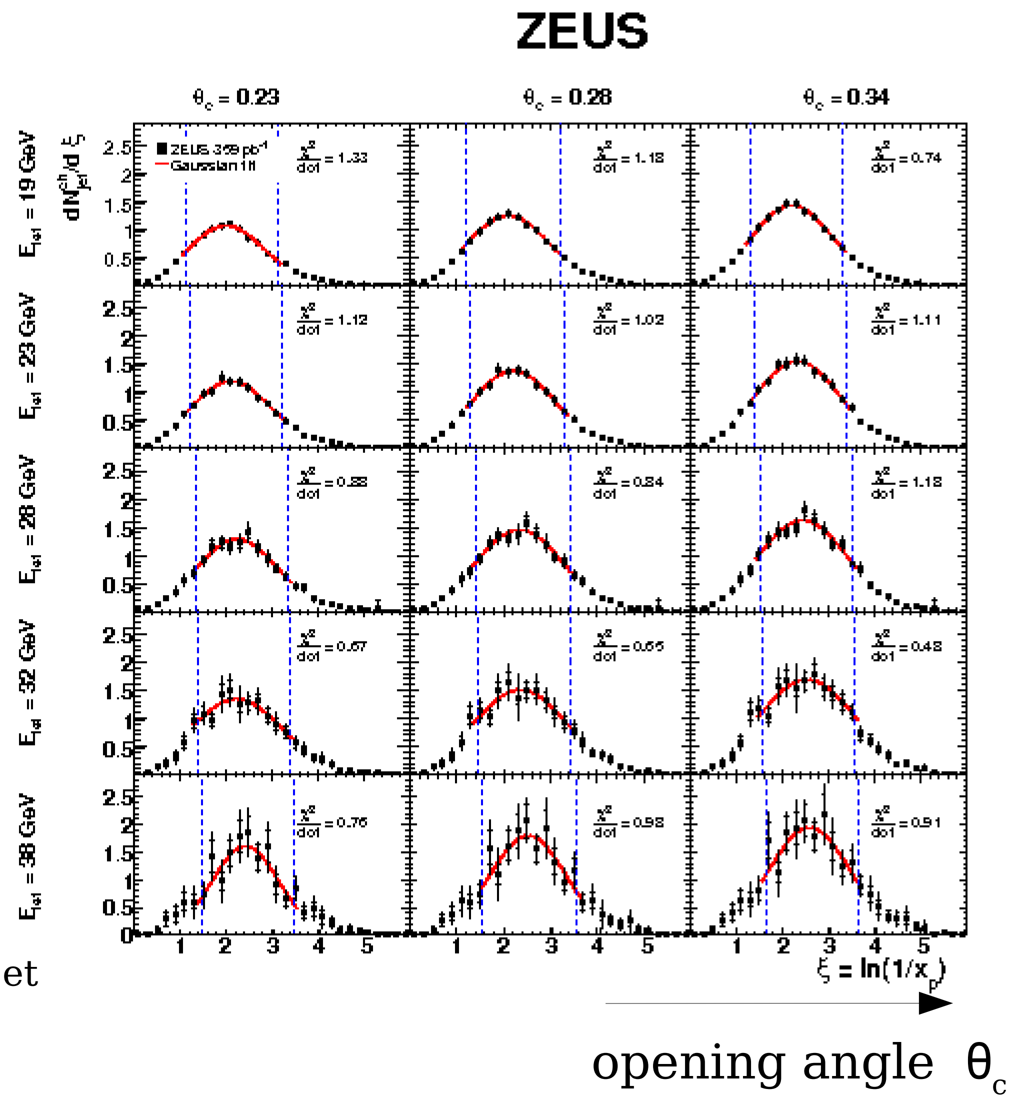
- Study fragmentation of jets
  non perturbative region of QCD
- Charged particles in jets: tracks with
  $p_t > 0.15$ GeV $|\eta| < 1.7$
- Prediction MLLA
  Modified leading log approximation
  includes all terms of $\alpha_s^n \log^{2n}(E_{init}^{pl})$ and $\alpha_s^n \log^{2n-1}(E_{init}^{pl})$
  describes momentum and multiplicity spectra of partons
  accounts for colour-coherence (angular ordering scheme)
  free parameter
  - Λ_{eff} effective energy scale, $Q_0 = \Lambda_{eff}$: lowest valid scale
- Scaled momentum variable $\xi(\theta_c, E^{jet})$
  $\xi = \ln(1/x_{chp})$
  x_{chp}: fraction of jet momentum



ZEUS arXiv:0904.3466v1 [hep-ex]

Scaled Momentum Distributions

Charged Particles in Dijet Events



$\xi(\theta_c, E^{jet})$ $\xi = \ln(1/x_{chp})$

x_{chp}:fraction of jet momentum

- similar in shape
- roughly Gaussian, upper tails
- Shape predicted by MLLA
- Fit: gaussian and MLLA

- 2005-2007, 359 pb^{-1}
- $0.2 \leq y_{jb} \leq 0.85$
- two jets with $|\eta_{jet}| \leq 1$

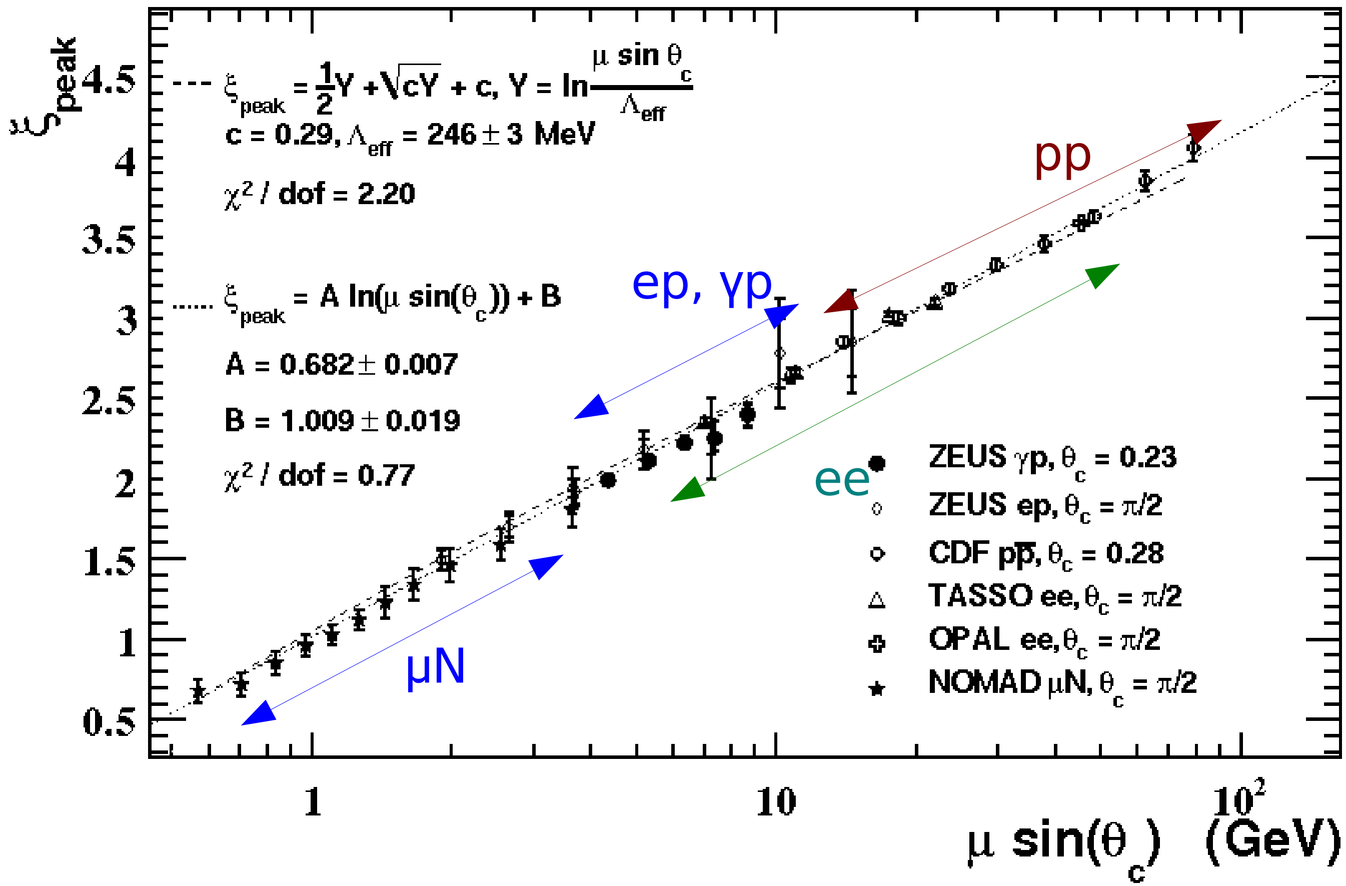
  $E_t^{jet1} \geq 17$ GeV, $E_t^{jet2}/E_t^{jet1} \geq 0.8$

  back-to-back $|\Phi^{jet1} - \Phi^{jet2}| \geq 0.9\pi$
- $x_\gamma^{obs} \geq 0.75$
- Tracks $p_t > 0.15$ GeV $|\eta| < 1.7$

ZEUS arXiv:0904.3466v1 [hep-ex]

Scaled Momentum Distributions

ξ_{peak} vs $\mu \sin(\theta_c)$, $\mu = E^{jet}$ characteristic energy scale



- $\xi_{peak} \approx A \cdot \ln(\mu \sin(\theta_c)) + B$
- MLLA small correction
- ZEUS γp alone below global fit
- MLLA fit: Λ_{eff}
  Λ_{eff} lowest valid scale
- Slight dependence on θ_c
- No dependence on energy

Λ_{eff} =values largely consistent with other experiments

ZEUS arXiv:0904.3466v1 [hep-ex]

Summary

- Dijets in photoproduction
  many QCD tests
  Sensitivity to photon and proton PDF
  well described by NLO calculation
  except azimuthal correlations

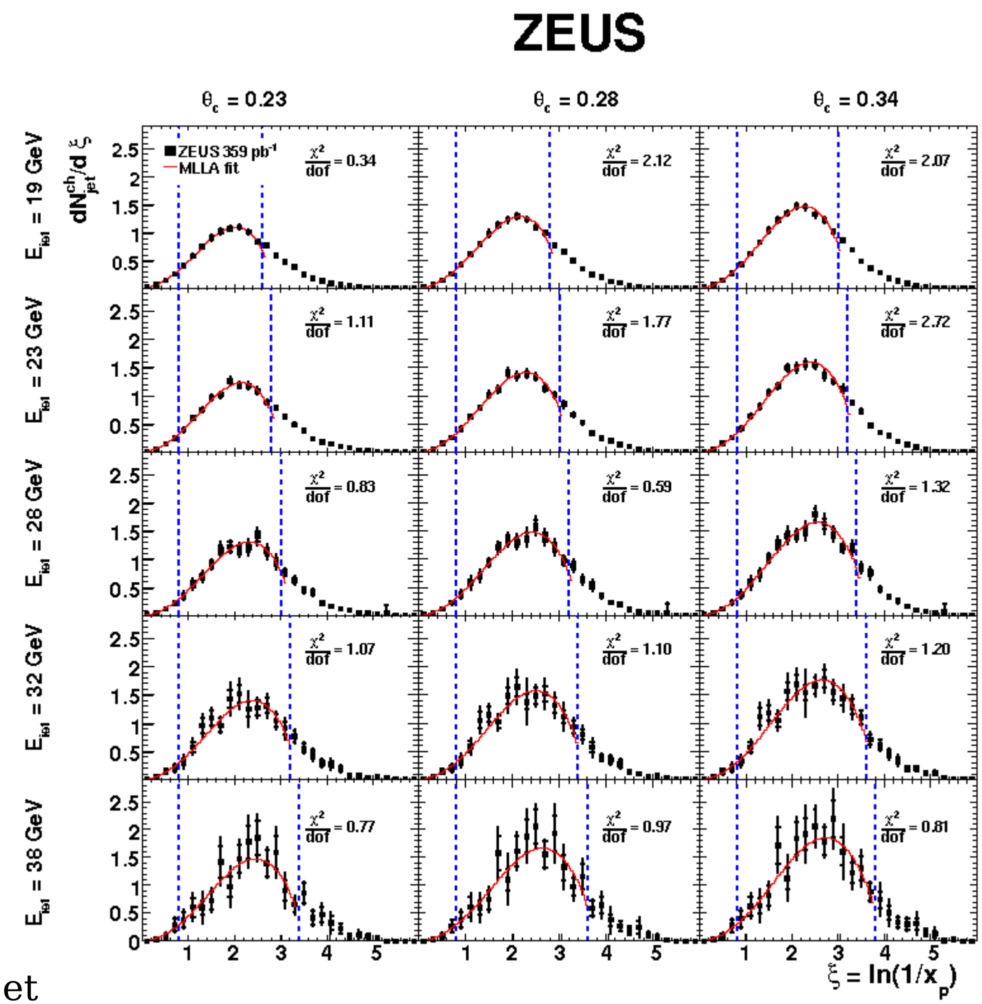
- Prompt photons in photoproduction
  NLO calculation and calculation based on kt factorisation
  description reasonably well
  problems in some kinematic regions

- Diffractive scattering of high $|t|$ photons
  $|t|$ dependence harder than expected from BFKL or VM production

- Scaled momentum distributions
  in agreement with MLLA with a universal scale Λ_{eff}

Backup slides

Scaled Momentum Distributions
Charged Particles in Dijet Events



E^{jet}

opening angle θ_c

$\xi(\theta_c, E^{jet})$ $\xi = \ln 1/x_p$

x_p: fraction of jet momentum

- similar in shape
- roughly Gaussian, upper tails
- Shape predicted by MLLA
- Fit: gaussian and MLLA

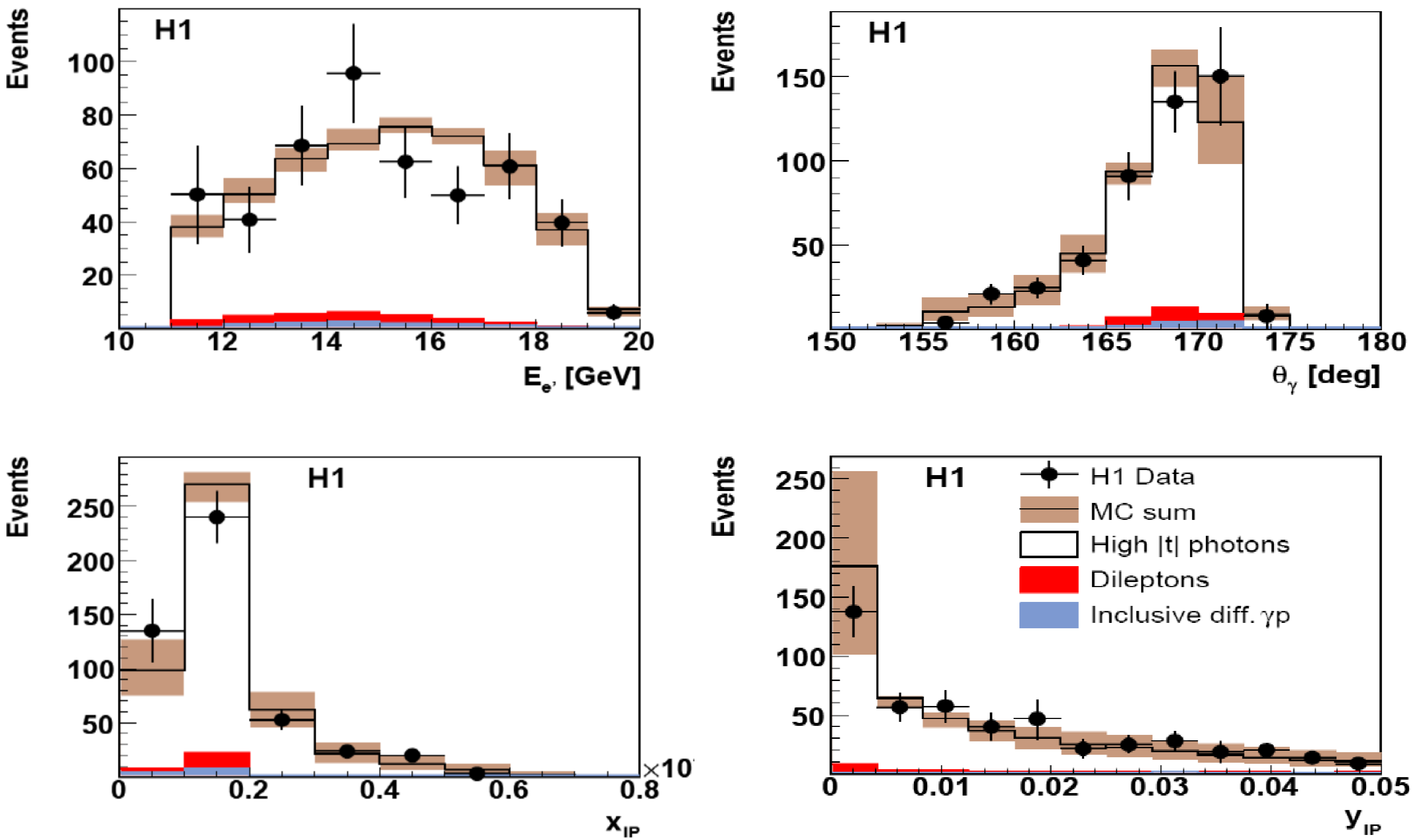
- 2005-2007, 359 pb^{-1}
- $0.2 \leq y_{jb} \leq 0.85$
- two jets with $|\eta_{jet}| \leq 1$

  $E_t^{jet1} \geq 17$ GeV, $E_t^{jet2}/E_t^{jet1} \geq 0.8$

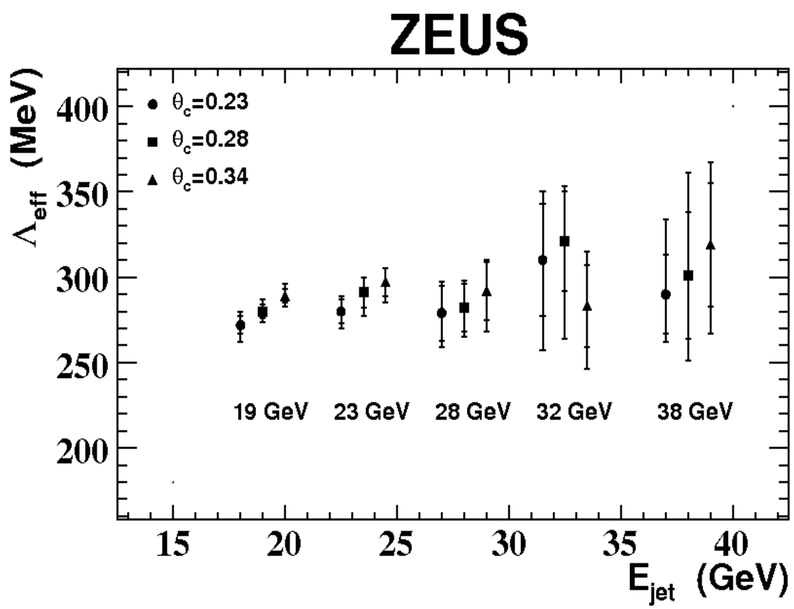
  back-to-back $|\Phi^{jet1}-\Phi^{jet2}| \geq 0.9\pi$
- $x_\gamma^{obs} \geq 0.75$
- Tracks $p_t > 0.15$ GeV $|\eta| < 1.7$

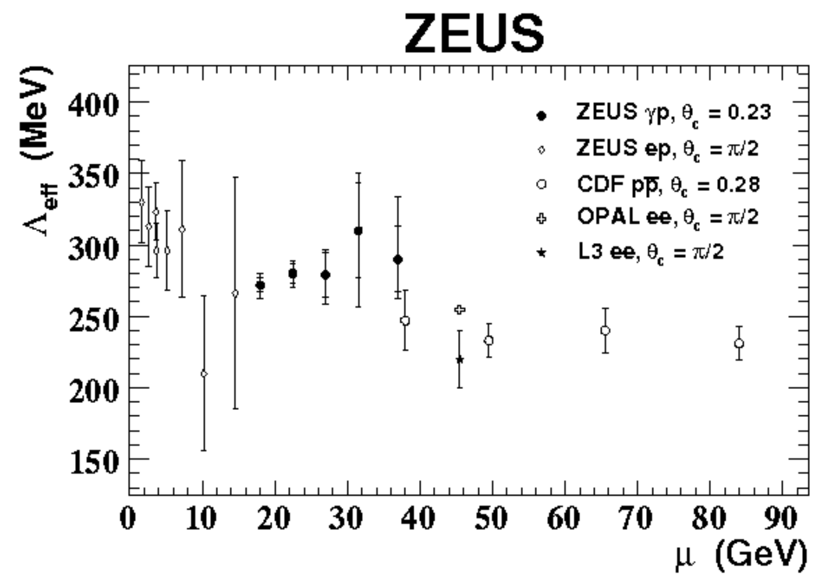
ZEUS preliminary

Diffractive Scattering of high t Photons



[arXiv:0706.3809 [hep-ex]]





Λ_{eff} from ξ_{peak}

$$\sigma_{peak} = \frac{1}{2} + \sqrt{cY} - c \quad c = 0.29$$

$$Y = \ln(E \sin(\Theta_c) / \Lambda_{eff})$$

- MLLA fit: Λ_{eff}
  Λ_{eff} lowest valid scale

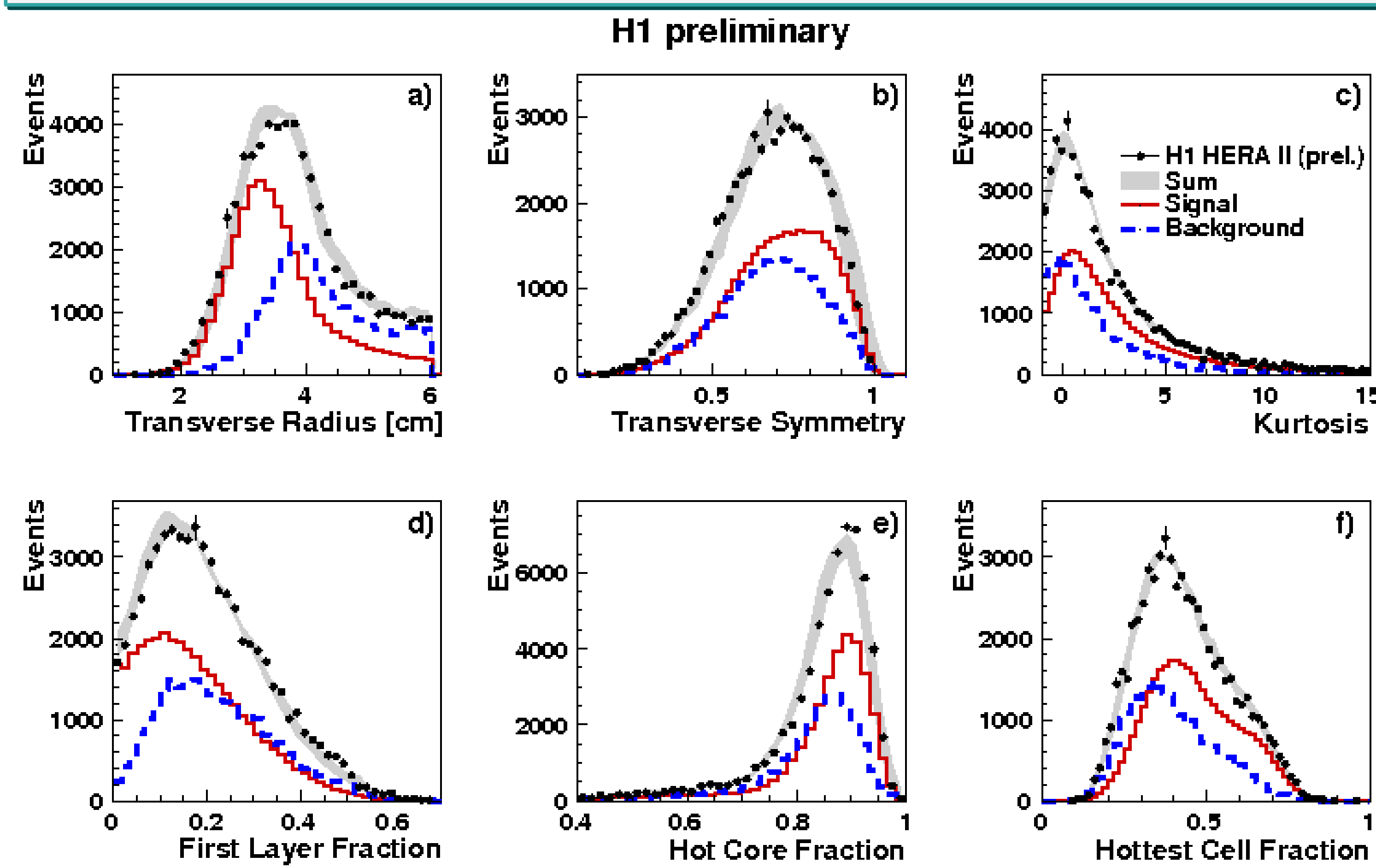
- Slight dependence on θ_c
- No dependence on energy

Λ_{eff} =values largely consistent with other experiments

ZEUS preliminary

Prompt Photons in Photoproduction

- Alternative access to x_γ and x_p
- Different systematics, smaller corrections for hadronisation
- New analysis extends to forward region
- Large background from neutral mesons



Shower shapes

Discriminator

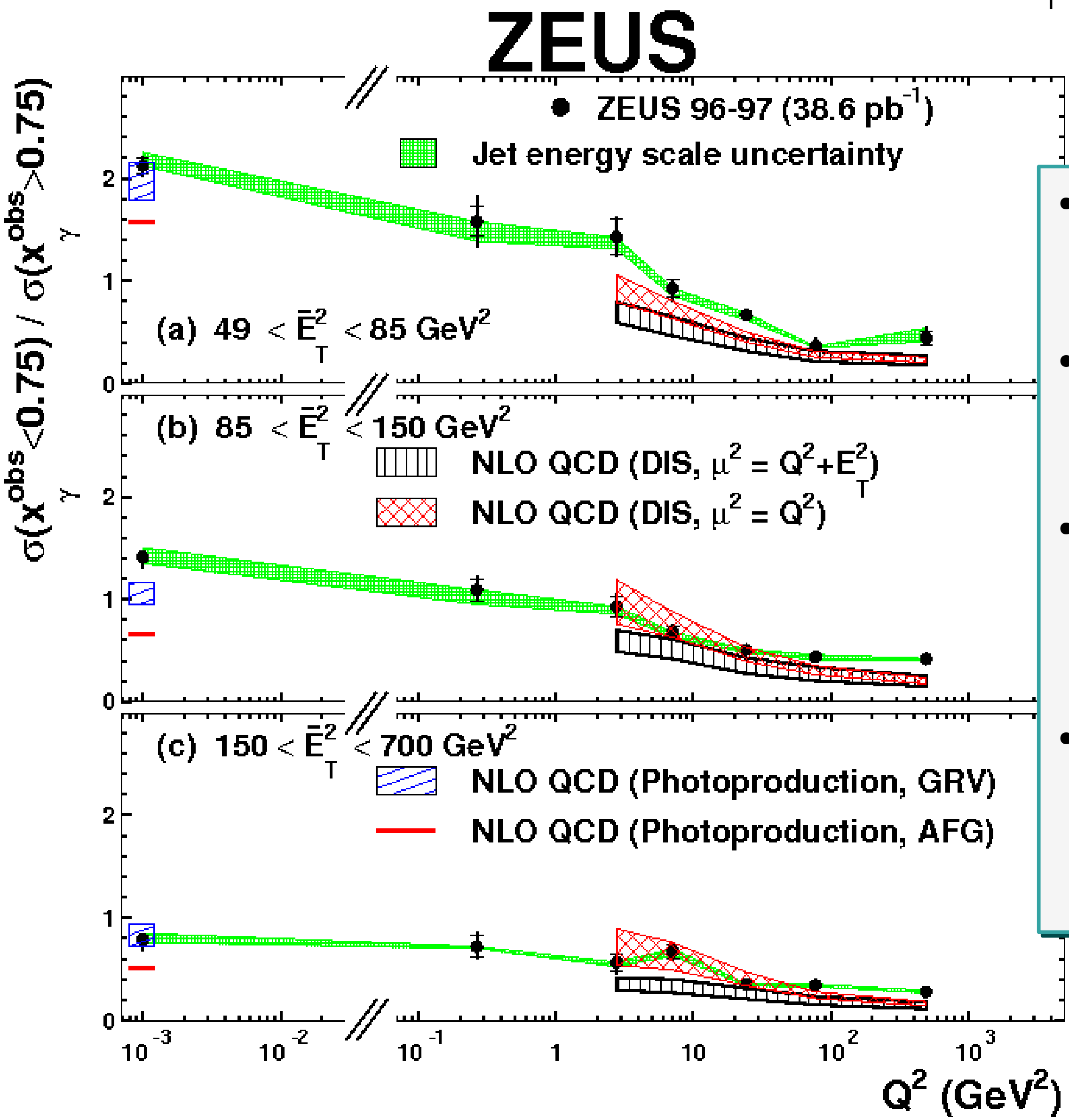
Unfold signal

Cross Sections

H1 preliminary 09-035 $6<E_T^\gamma < 15$ GeV, $-1.0<\eta^\gamma<2.43$, $0.1<y<0.7$, $4.5< E_t^{jet}$, $-1.3<\eta^{jet}<2.3$

Resolved component, $R=\sigma(x_\gamma^{obs}<0.75)/\sigma(x_\gamma^{obs}>0.75)$

Ratio R as a function of Q^2 for different E_T^2



- Several experimental and theoretical uncertainties cancel
- Supression of resolved component with Q^2 and E_T^2
- NLO calculations for $Q^2 \approx 0$ AFG underestimates resolved cont. GRV reasonable description
- NLO calculation for $Q^2>0$ scale Q^2 preferred some suppression visible

hep-ex/0404033 ZEUS: 38.6 pb^{-1} ,$0<Q^2<2000$ GeV^2 jets: $-3<\eta^{\gamma p}<0$, $E_T^{Jet1}>7.5$ GeV, $E_T^{Jet2}>6.5$ GeV